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CALIBRATION OF HYDRAULIC FORCE MACHINES – REQUIREMENTS, CONCEPTS, PROBLEMS, SOLUTIONS

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Abstract – Modern building technologies (for example prestressed concrete to produce beams, floors, bridges, or installation, testing and monitoring of ground anchors) require the use of accurate force machines (hydraulic jacks). One component of successful building works is a correct and accurate calibration procedure of hydraulic jack for tensioning cables or anchors. This article analyzes two different calibration methods: By means of hollow load cell and thread bar and calibration in the closed frame.

We analyze these methods using different accessories and their influence on the uncertainty of calibration results. As a very important part of calibration procedure is a correct choice of the calibration mathematical model (interpolation curve *force-hydraulic pressure* and *hydraulic pressure-force*), there is a need to use a special software. Such is the developed software **FORCE-401-S** which permits to communicate the measurement line "load cell-amplifier-computer"; to choose the correct interpolation polynom; enable to compute the errors and uncertainty values and build the table of calibration results.

The calibration procedure is performed according to the standard ISO 7500-1 "Verification of static uniaxial testing machines - Part 1: Tension/compression testing machines - Verification and calibration of the force-measuring system". We recommend to widen the definitions of this standard and to include calibration of non-force units scaled devices (as an example pressure gauges).

Keywords: force calibration, interpolation, uncertainty.

1. FORCE MEASUREMENT-METHODS, ACCESSORIES

Building technologies requires very wide range of hydraulic jacks both in terms of capacity (from 2 ton force to 500 ton force) and working prestressing technology (one steel cable, some steel cables, thread bar).

Calibration of jacks with loading force capacity up to 20 ton performed by means hollow Load Cell C6A HBM ***1*** and set accessories: steel cable ***2*** as a loading element, spherical cap ***3*** and centering elements ***4*** (Fig. 2). For the calibration of jacks with loading capacity up to 100 tons used the same measurement method, but instead of steel cable, the thread bar ***5*** used as a loading element.

The spherical cap and two accessories ***4*** ensure coaxial loading, except non-coaxial forces and reduce the measurement uncertainty. According to our research the uncertainty values are in Table 1.

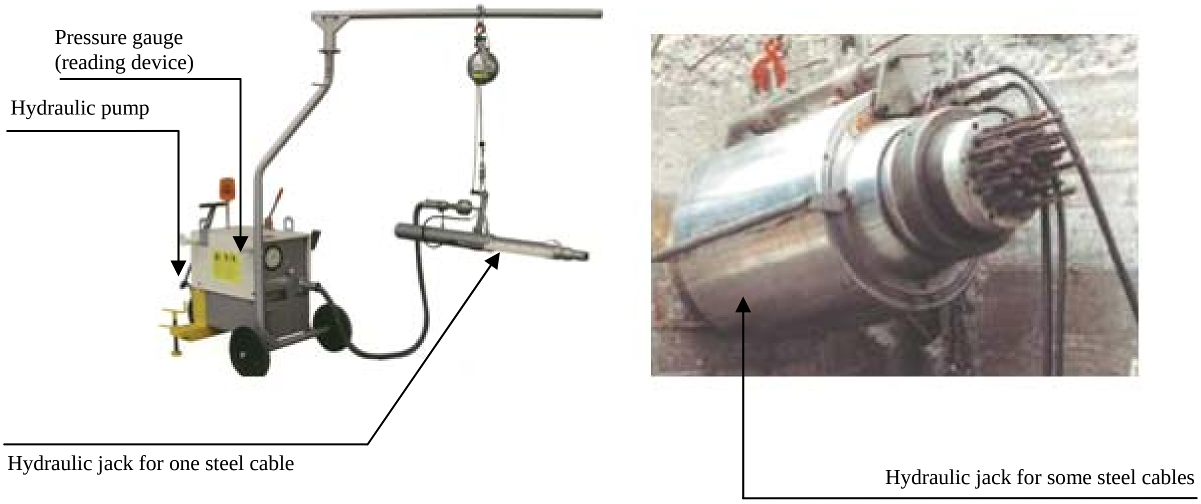


Fig. 1. Hydraulic Jack.

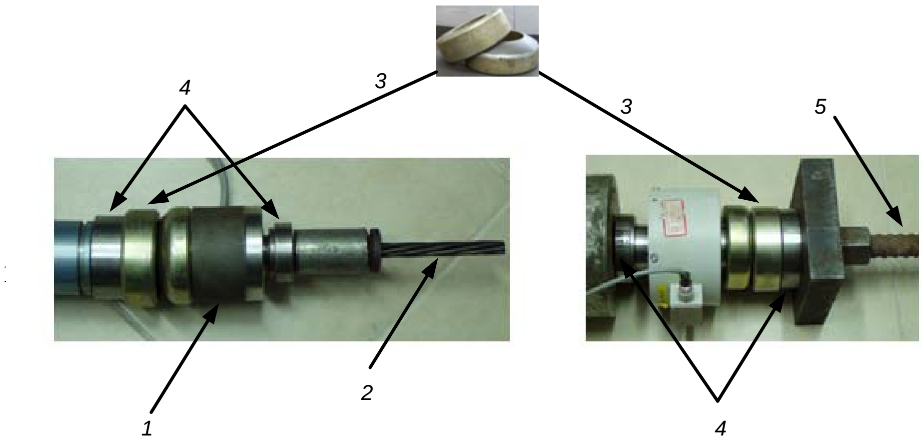


Fig. 2 Calibration by means of steel cable.

Fig. 3 Calibration by means of thread bar.

Table 1. Uncertainty values.

	Calibration with spherical cap	Calibration without spherical cap
Uncertainty	$0.2\% \div 0.6\%$ *	$0.5\% \div 1.2\%$ *

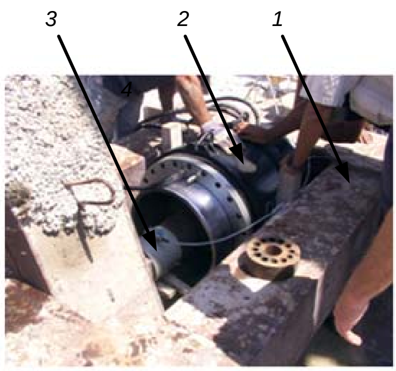
*of reading value

T Calibration of jacks with loading capacity of up to 500 tons performed by means different methods:

Loading and measuring in horizontal closed frame (Fig. 4): ***1*** is an horizontal frame, ***2*** is an hydraulic jack, ***3*** is a Load Cell;

Loading and measuring by several steel cables (Fig. 5): ***1*** are steel cables, ***2*** is an hydraulic jack, ***3*** is a hollow Load Cell;

Loading and measuring in vertical closed frame (Fig. 6): ***1*** is a vertical frame, ***2*** is an hydraulic jack, ***3*** is a Load Cell



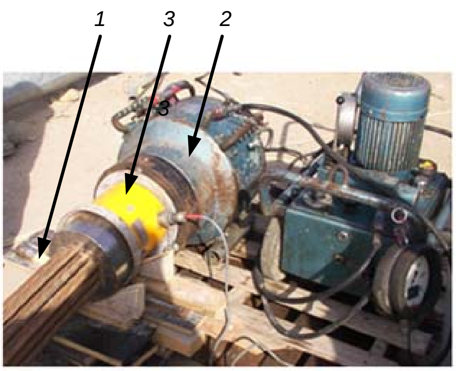


Fig. 4. Loading and measuring in horizontal closed frame.

Fig. 5. Loading and measuring by several steel cables.

Fig. 6. Loading and measuring in vertical closed frame.

(a) Disadvantages of this method are:
- A long preparation time of calibration system;
- A special form of spherical cap is required;
- Difficulties of coaxial mounting of all elements (jack, Load Cell and spherical cap);
- Low measurement uncertainty values.
- Due to that, this the method is practically unused.

(b) Substantial advantages of this method are:
- The calibration process is similar to prestressing working process;
- The hollow form of Load Cell allows for performance calibration without special accessories and ensures coaxial loading of all elements of measurement (calibration) system.
- The disadvantage of this method is a low accuracy of the hollow Load Cells.

(c) The advantages of this method are:
- A short preparation time of calibration system;
- The possibility of using relatively high accuracy Load Cells;
- Relatively high measurement uncertainty.

2. CALIBRATION RESULTS-INTERPRETATION

One feature of prestressing machines (hydraulic jacks) is their inability to read the force value (the reading device is pressure gauge) –due to that, the calibration results presented in an "applied force-reading" form. In this situation, error accuracy estimation is problematic (we cannot compare of force values with pressure gauge reading) and the classical formulae of deviation value is not used.

For solve this problem, P.K. Labs developed the software **FORCE-401-S** which according to calibration results grants the "Least Sum of Squire" method to build the analytical curve $F = f(R)$, where F -is the applied force and R - reading of the pressure gauge and computes the relative interpolation error q as an accuracy estimation:

$$q = \frac{F_A - F_T}{F_T} \cdot 100\%,$$

where

F_T - is a theoretical (computed) force value from interpolation equation;

F_A - is an applied (measured by means of Load Cell) force.

The software includes four options of choice of the interpolation curve:

1. Interpolation polynom of 1^{st} degree: $F = aR + b$;
2. Interpolation polynom of 2^{nd} degree: $F = aR^2 + bR + c$;
3. Interpolation polynom of 3^{rd} degree: $F = aR^3 + bR^2 + cR + d$;
4. The software automatically chooses the degree of interpolation according to minimal interpolation error.

It is understood that each calibrated device has different technological and technical deviation, such as friction between piston (rod) and cylinder, high temperature of oil in the hydraulic system, roundness deviations of piston and cylinder and its fitness. All of these factors influence the values of interpolation coefficients. Our experiments confirm that calibration curve doesn't intersect the "zero point" of coordinate system ***"force-pressure".*** Fig.7 demonstrates different forms and characteristics of parabolas.

The character of interpolation curve and his location requires:

1. Defining the correct lower limit of the measurement range;
2. Adding to the calibration table of two interpolation equations: $F = f(R)$ and inverse function $R = f(F)$.

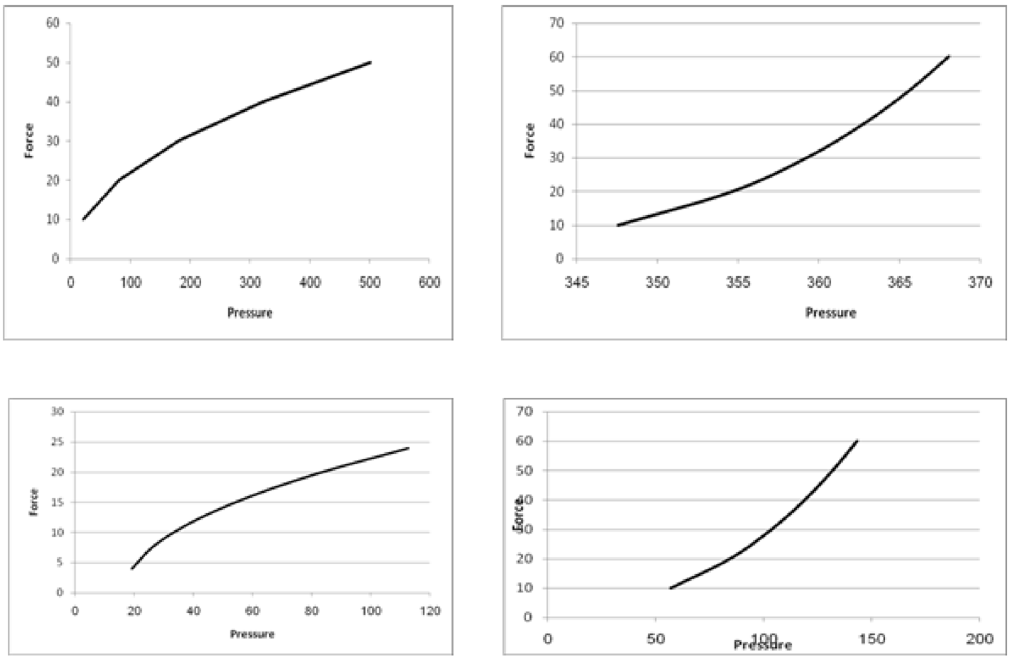


Fig. 7. Interpolation curves.

3. CALIBRATION CERTIFICATE - STANDARDIZATION

The International standard ISO 7500-1:2004 defines the calibration requirements of force testing machines, as a scale reading device which is expressed in **units of force**. Based on our research and work experience we recommend to include to the International Standard ISO 7500-1:2004 also requirements for prestressing machines (hydraulic jacks), where the reading scale device is expressed in units of pressure and to classify accuracy classes.

The following tables (as an examples) demonstrate the calibration table according to this standard (accuracy class 1 on Fig.8 and accuracy class 3 on Fig.9).

Reading	Applied force	Deviation of interpolation	Repeatability	Relative resolution	Uncertainty
R	F	q	b	a	U
bar	tf	%			
50	1.90	0.07	0.46	0.50	0.69
100	3.97	-0.12	0.41	0.25	0.40
150	6.06	0.03	0.41	0.17	0.34
200	8.17	0.10	0.12	0.13	0.19
250	10.33	-0.09	0.31	0.10	0.24
320	13.37	0.02	0.22	0.08	0.19

Interpolation equations:

$F = aR^2 + bR + c$

a=5.594E-06
b=4.042E-02
c=-1.327E-01

$R = kF^2 + lF + m$

k=-7.288E-02
l=2.464E+01
m=3.398E00

Fig. 8 Calibration results (example).

Reading	Applied force	Deviation of interpolation	Repeatability	Relative resolution	Uncertainty
R	F	q	b	a	U
bar	tf	%			
50	1.90	-2.83	0.46	0.50	1.28
100	3.97	0.03	0.41	0.25	0.79
150	6.06	0.68	0.41	0.17	0.50
200	8.17	0.65	0.12	0.13	0.29
250	10.33	0.12	0.31	0.10	0.26
320	13.37	-0.41	0.22	0.08	0.20

Interpolation equations:

$F = aR + b$

a=4.249E-02
b=-2.772E-01

$R = kF + l$

k=-2.353E+01
l=6.544E00

Fig.9 Calibration results (example).

4. CONCLUSIONS

1. P.K. Calibration laboratory has the technical, metrological and mathematical base to perform calibration of hydraulic jacks of different load ranges.
2. Calibration certificate of hydraulic jacks contains the measurement results table and two Interpolation equations:
    - force as a function of pressure;
    - pressure as a function of force.
3. The calibration results table is built according to the definitions and requirements of the International Standard ISO 7500-1:2004.
4. Our recommendation is to extend the International Standard ISO 7500-1:2004 for non–force units scaled devices (as an example pressure gauges) and to classify prestressing machines (hydraulic jacks) for accuracy grades according to this standard.

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